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COMPUTER MODELING OF LARGE ASTEROID IMPACTS INTO CONTINENTAL AND OCEANIC SITES: ATMOSPHERIC, CRATERING, AND EJECTA DYNAMICS; D.J. Roddy, U.S. Geological Survey, Flagstaff, Arizona; S.H. Schuster, M. Rosenblatt, L.B. Grant, P.J. Hassig, and K.N. Kreyenhagen, California Research and Technology, Chatsworth, Calif.

Numerous impact cratering events have occurred on the Earth during the last several billion years that have seriously affected our planet and its atmosphere [1]. The largest cratering events, which were caused by asteroids and comets with kinetic energies equivalent to tens of millions of megatons of TNT, have distributed substantial quantities of terrestrial and extraterrestrial material over much or all of the Earth [2,3]. Ejection of such massive quantities of vaporized and solid material can produce severe physical and chemical contamination of the atmosphere, which in turn may induce changes in the world's climate and biosphere [4,5]. In addition, large impacts may stimulate secondary volcanism to the extent that it releases as much or more volcanic ash and gas than the combined masses of impactor and crater ejecta. Large impacts in the oceans can also produce tidal waves rising kilometers in height that can severely effect coastal and near-coastal regions. Separately or collectively, these impact effects can have global consequences.

In order to study a large-scale impact event in detail, we have completed computer simulations that model the passage of a 10-km-diameter asteroid through the Earth's atmosphere and the subsequent cratering and ejecta dynamics associated with impact of the asteroid into two different targets, i.e., an oceanic site and a continental site [6]. The calculations were designed to (1) broadly represent giant impact events that have occurred on the Earth since its formation and (2) specifically represent an impact cratering event proposed to have occurred at the end of Cretaceous time.

In our calculations, the asteroid was modeled as a spherical body moving vertically at 20 km/s with a kinetic energy of 2.6×10^{30} ergs (6.2×10^{7} Mt). Detailed material modeling of the asteroid, ocean water, crustal rock units, sedimentary rock unit, and mantle included effects of strength and fracturing, generic asteroid and rock properties, porosity, saturation, lithostatic stresses, and geothermal contributions; all modeling was designed to simulate impact and geologic conditions as realistically as possible. For example, the sedimentary unit was modeled to represent a combination of shale, sandstone, and limestone with 17% porosity and water saturation; details for the other units are given in [6].

Calculation of the passage of the asteroid through a U.S. Standard Atmosphere showed development of a strong bow shock that expanded radially outward. Behind the shock front was a region of highly shock compressed and intensely heated air. Behind the asteroid, rapid expansion of this shocked air created a large region of very low density (<0.001 bar) that also expanded away from the impact area. Peak air temperatures were calculated to be ~20,000 K above the rim at a range of 15 km at 2 s after impact. By ~4.5 s the rim had uplifted to ~10 km at 15 km range and the air temperature above the rim was calculated to be ~10,000 K. At 30 s air temperatures were still over ~2,000 K at ground level at ranges of ~100 km. Calculations to 30 s showed that the shock front in the air and most of the expanding shocked air mass preceded formation of the crater, its ejecta, and rim uplift and had moved radially outward and did not interact with these ground features.

Calculations of the cratering events in both the continental and oceanic targets were carried to 120 s. Despite geologic differences, impacts in both targets developed comparable dynamic flow fields, and by ~29 s similar-sized transient craters ~39 km deep and ~62 km across had formed. In the oceanic impact, transient-rim uplift of ocean and underlying crust reached a maximum altitude of nearly 40 km at ~30 s; this uplifted mass then collapsed with radial velocities of ~500 m/s to produce enormous tsunamis. After ~30 s, strong gravitational rebound drove craters in both oceanic and continental targets toward broad flat-floored shapes. At 120 s, transient crater diameters were ~80 km (continental) and ~105 km (oceanic) and transient depths had risen to only ~27 km; crater floors consisting of melted and fragmented hot rock continued to rebound rapidly upward. By 60 s, $\sim 2 \times 10^{14}$ t was ejected from the continental

crater, about twice the mass ejected from the oceanic crater; the difference is due to the greater density of rock versus water. By 120 s, ~70,000 km^3 (continental) and ~90,000 km^3 (oceanic) of target material were excavated (no mantle), and massive ejecta blankets were forming around the craters. We estimate that more than 70% of the ejecta would finally lie within about three crater diameters of the impact, but the remaining ejecta (~10^{13} t), including the vaporized asteroid, would be lofted to altitudes at least as high as ~100 km.

For all practical purposes, the atmosphere was nearly completely removed from the impact area for tens of seconds, i.e., air pressures were less than fractions of a bar out to ranges of over 50 km. Consequently, much of the asteroid and target materials were ejected upward into a near vacuum. For comparison with the amount of ejecta, the original column of displaced air weighed ~10^{11} t. Velocities of the ejecta vapor from the oceanic impact were sufficient to lift ~9 x 10^{12} t to altitudes of ~80 km and higher (original ionosphere level), ~1 X 10^{13} t to an altitude of ~30-80 km (orginal mesosphere level), and ~1.5 X 10^{13} t to an altitude of ~13-30 km (original stratosphere level). Most of this very hot ejecta vapor consisted of ocean water combined with a smaller amount of crustal material estimated at <10% of the total. The altitude distribution of ejecta from the continental impact was similar to that from the oceanic impact: ~7 X 10^{12} t to ionospheric levels, ~9.0 X 10^{12} t to mesopheric levels, and ~1.6 X 10^{13} t to stratospheric levels. We estimated that over 90% of these ejecta came from the sedimentary unit. Calculations indicate that ~1 X 10^{12} t of vapor was ejecta from the sedimentary unit of the continental crater. All of the asteroid vaporized, but in both impact events its mass was less than ~1% of the total mass of the target materials ejected. By 60 s, ~5 X 10^{11} t of vaporized asteroid had been ejected above 13 km, the original level of the tropopause, by the oceanic impact and ~6 X 10^{11} t by the continental impact. The total mass of asteroid vapor ejected to all altitudes by 60 s was equal to ~6.8 X 10^{11} t for the oceanic impact and ~9 X 10^{11} t for the continental impact, i.e., ~52% and 70%, respectively. By 120 s, virtually all of the asteroid was expanding upward from the crater as vapor.

Effects of secondary volcanism and return of the ocean over hot oceanic crater floor could also be expected to add substantial solid and vaporized material to the atmosphere, but we have not studied these conditions.

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